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CORRECTION OF UBV PHOTOMETRY FOR EMISSION LINES

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Abstract. We investigated the effect on the U, B, V magnitudes of the removal of the emission lines from the spectra of some symbiotic stars and novae during their nebular phases. We approached this problem by a precise reconstruction of the composite UV/optical continuum and the line spectrum. Corrections ΔU, ΔB, ΔV are determined from the ratio of fluxes with and without emission lines. Here we demonstrate this effect on the case of the symbiotic nova V1016 Cyg during its nebular phase. We find that about 68%, 78% and 66% of the observed flux in the U, B and V filters is radiated in the emission lines. The effect should be taken into account before using the observed color indices of emission-line objects for diagnosis of their radiation in the continumm.

Key words: techniques: photometric – stars: emission lines – stars: binaries: symbiotic

1. INTRODUCTION

Photometric measurements in the standard U, B, V filters are often used to analyze radiation in the continuum of many kinds of stellar objects. A diagnostic by the ($U-B$, $B-V$)-diagram is frequently applied to compare the observed colour indices to those of the continuum radiation from main-sequence stars, supergiants, a blackbody and/or a nebula. However, the true continuum is often affected by the line spectrum, which thus requires corrections of the photometric observations before studying the continuum radiation. For example, the presence of emission lines in the spectral region of the U, B, V passbands leads to *brighter* magnitudes than those of the continuum.

In this contribution we introduce the effect on the U, B, V magnitudes due to the removal of emission lines from the spectrum. However, a strong variation of the emission spectrum due to the activity, large differences between individual objects and a complex profile of the true continuum for emission-line objects preclude a simple solution. Hither-to, this problem has been approached only by a few groups of authors and without giving any concept for a general application (see, e.g., Fernandez-Castro et al. 1995)

Here we quantify corrections of the U, B, V photometry for emission lines by exact calculations of the predicted spectrum. We demonstrate this effect on the case of symbiotic nova V1016 Cyg, which spectrum is very rich to numerous strong emission lines during its nebular phase.

2. ANALYSIS

2.1. The method

The aim of this paper requires the ratio of the continuum with the superposed emission lines to the line-removed continuum at all relevant wavelengths. Thus we need the profile of the continuum and the emission line spectrum obtained (in the ideal case) simultaneously with the photometric observations.

To quantify the effect of emission lines on the U, B, V measurements, we express the observed flux in the form

$$F_{\rm obs}(\lambda) = F_{\rm cont}(\lambda)(1+\epsilon(\lambda)), \tag{1}$$

where $F_{\rm cont}(\lambda)$ is the true continuum (i.e. line-removed continuum) and $\epsilon(\lambda)$ represents the emission line spectrum in units of the continuum at the wavelength λ. Then the magnitude difference, Δm, between the observed magnitude, $m_{\rm obs}$, and the magnitude of the true continuum, $m_{\rm cont}$, can be expressed as

$$\begin{gathered}\Delta m = m_{\rm obs} - m_{\rm cont} = \\ -2.5\log\left[\int_\lambda F_{\rm cont}(\lambda)S(\lambda)(1+\epsilon(\lambda))\,{\rm d}\lambda \Big/ \int_\lambda F_{\rm cont}(\lambda)S(\lambda)\,{\rm d}\lambda\right],\end{gathered} \tag{2}$$

where $S(\lambda)$ are transmission functions of the U, B, V filters. Further we approximate the emission line spectrum with an ensemble of

Gauss functions, $G_{\rm i}$, as

$$\epsilon(\lambda) = \sum_i G_{\rm i}(\lambda; \lambda_{\rm i}, I_{\rm i}, \sigma_{\rm i}), \qquad (3)$$

where $\lambda_{\rm i}$ is the wavelength of the i-*th* line, $I_{\rm i}$ its maximum in units of the local continuum and $2\sigma_{\rm i}$ its FWHM. According to the relation (2) the removal of emission lines from the spectrum gives *fainter* magnitudes at all wavelengths. A main difficulty in calculating corrections Δm is connected with reconstruction of the continuum profile, $F_{\rm cont}(\lambda)$, which can be rather complex in the case of the composite continuum of symbiotic stars. We introduce briefly this problem in Sect. 2.3. We reconstructed the line spectrum, $\epsilon(\lambda)$, according to its parameters available in the literature (fluxes and the continuum level). Example is given below in Sect. 2.4.

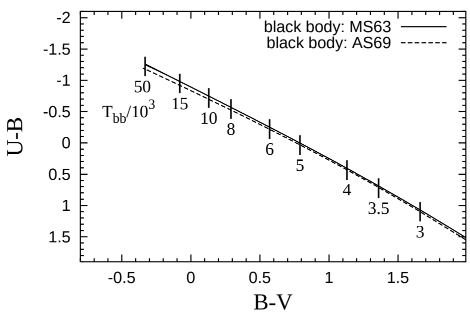

Fig. 1. Comparison of the blackbody colour indices calculated according to Eq. 5 (solid line, Matthews & Sandage 1963) and Eq. 6 (dashed line, Ažusienis & Straižys 1969).

2.2. Calculated $U-B$ and $B-V$ colours

The colours on the U, B, V system can be determined once the transmission functions $S(\lambda)$ of the system are known. Theoretical colours $(U-B)_0$ and $(B-V)_0$ can be calculated as

$$(U-B)_0 = -2.5 \log \left[\int_\lambda F(\lambda) S_{\rm U}(\lambda)\, {\rm d}\lambda \Big/ \int_\lambda F(\lambda) S_{\rm B}(\lambda)\, {\rm d}\lambda \right] \qquad (4)$$

with a similar equation for the $(B-V)_0$ index. The aim is to obtain such $U-B$ and $B-V$ indices, which would predict the observed colours for real stars of known energy distribution. This task requires additional colour equations, which are used to convert theoretical calculations based on the adopted $S(\lambda)$ to the empirical U, B, V system. Matthews & Sandage (1963) derived these equations as

$$B-V = 1.024(B-V)_0 + 0.81, \quad U-B = 0.921(U-B)_0 - 1.308, \quad (5)$$

which correspond to $S(\lambda)$ from their Table A1. Later on, Ažusienis & Straižys (1969) suggested the following relations

$$B-V = (B-V)_0 + 0.67, \quad U-B = (U-B)_0 - 1.33, \qquad (6)$$

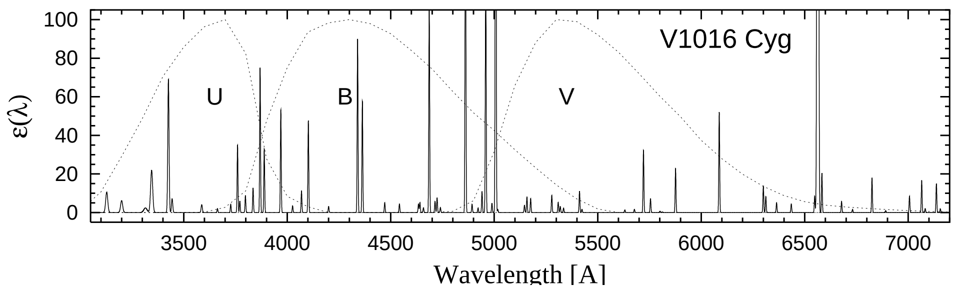

Fig. 2. Function $\epsilon(\lambda)$ for the symbiotic nova V1016 Cyg, which represents its emission line spectrum in units of the continuum. Dotted lines show normalized transmission functions of the U, B, V filters.

for their set of the revised response functions (see their Table 1). We compared both transformations on the example of the blackbody colour indices (Figure 1). Both transformations give very close values, and in this paper we use only the Matthews & Sandage (1963) equations.

2.3. The composite continuum

We reconstruct the continuous radiation, $F_{\rm cont}(\lambda)$, of symbiotic binaries by a three-component model, which consists of two stellar components of radiation – from the hot and the cool star – and the nebular radiation from the ionized circumbinary medium (e.g. Nussbaumer & Vogel 1989). We approach this problem with the aid of low-resolution IUE spectra and the broad-band infrared photometry. The latter was approximated by synthetic spectra for red giants according to models of Hauschildt (1999) to get the infrared stellar continuum. Then, on the basis of such defined continuum, we applied the three-component model of radiation of symbiotic stars to get the profile of the continuum in between these regions (see Skopal 2001, 2003 for more details).

2.4. The emission line spectrum

Figure 2 shows example of the $\epsilon(\lambda)$ function from Eq. 1, which represents the emission line spectrum of the symbiotic nova V1016 Cyg. To reconstruct this function we used emission line fluxes published by Schmid & Schild (1990) (hereafter SS90). The spectrum was taken on 15/11/87 at the INT telescope.

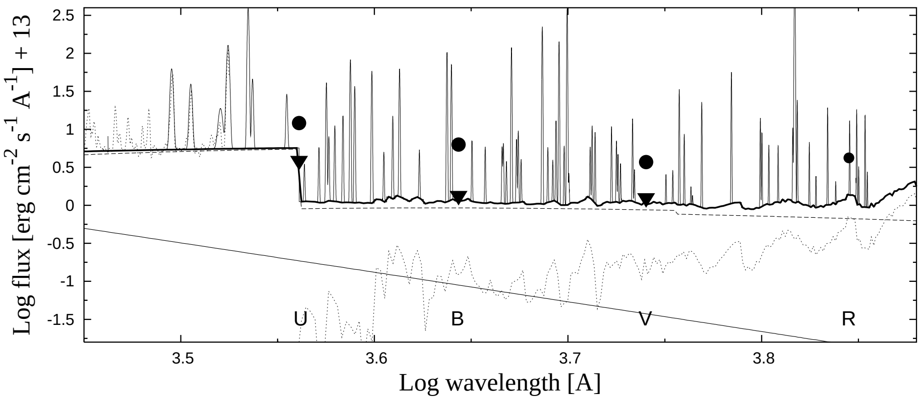

Fig. 3. Reconstructed SED in the near-UV/optical continuum of the symbiotic nova V1016 Cyg. Solid thin line represents radiation from the hot object ($T_{\rm h} = 150000$ K), dashed line is that from the nebula ($T_{\rm e} = 16800$ K) and the solid thick line is the resulting modeled continuum. Radiation from the giant was compared with the synthetic spectrum and scaled to the flux in the J band (see the text). The emission line spectrum was introduced in Fig. 2. Full circles are fluxes given by the broad-band photometry. Triangles are the U, B, V magnitudes corrected for the emission lines.

3. THE EXAMPLE OF V1016 Cyg

V1016 Cyg is a symbiotic nova, which erupted in 1964 when it brightened by about 5 mag in the optical and has continued a very slow decrease of its brightness (Parimucha et al. 2000). It belongs to the D-type symbiotics (strong IR dust emission) and contains a Mira variable as cool component (SS90 and references therein). According to the ultraviolet (IUE) and optical (INT) observations, the near-UV/optical spectral region was dominated by the nebular continuum superposed with strong emission lines at high excitation/ionization degrees (SS90).

To reconstruct the optical continuum of V1016 Cyg we used the IUE spectra SWP24655 and LWP04959 taken on 10/12/84 and the synthetic spectrum for the red giant with $T_{\rm eff} = 3\,100$ K and $\log(g) = 0.5$ (Hauschildt et al. 1999). The latter was scaled to the observed flux in the J-band, which is assumed to be free of any dust emission. The emission line spectrum is shown in Fig. 2 and was described in Sect. 2.4. All observations here were dereddened for interstellar extinction with $E_{\rm B-V} = 0.28$ (SS90).

Results are drawn in Fig. 3. Our model confirms a strong con-

tribution from the symbiotic nebula to the optical wavelengths. Applying our procedure described in Sect. 2 we found that the removal of emission lines makes the star's brightness fainter by 1.23, 1.67 and 1.18 mag in the U, B and V band, respectively. This means that V1016 Cyg emitted about 68%, 78% and 66% of the total light throughout the emission lines in these passbands. The corrected fluxes fit perfectly the predicted continuum. In addition, the effect is different in different passbands, which results in the relevant change of the colour indices. We calculated the empirical indices according to Eqs. 4 and 5. By this way we determined quantities $(U-B)$ = -1.27, $(B-V)$ = +0.03 for the observed spectrum (i.e. including lines) and $(U-B)_{\rm cont}$ = -1.68, $(B-V)_{\rm cont}$ = +0.53 for the modelled continuum. This results in a rather significant change in the colour indices, $\Delta(U-B) = 0.41$ and $\Delta(B-V)$ = -0.50. Therefore, it is necessary to remove the excess due to emission lines from the U, B, V magnitudes before using any diagnostic by colour indices.

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